Hurricane Florence Flooding in Georgetown County: A Qualitative Explanation of the Interactions of Estuary and Tidal River

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Abstract. This paper examines data from 18 USGS gauges in the lower Pee Dee Basin in an effort to explain the behavior of the flooding following Hurricane Florence (2018) in Georgetown County, South Carolina. Despite record or near-record flooding in all the tributaries to the Winyah Bay estuary, water levels near the city of Georgetown were well below predicted heights. Floodplain storage in the lower Great Pee Dee, Lynches, and Little Pee Dee River valleys stored over 1.2 million acre-feet of floodwaters, delaying peak stage near Bucksport for five days and reducing peak flow into the Winyah Bay tidal river/estuary system by nearly 50%. An unknown amount of flow from the Winyah Bay tidal river/estuary system flowed through the Atlantic Intracoastal Water Way to Little River rather than through Winyah Bay. The resulting freshwater flow to Winyah Bay only moved the point of tidal stagnation (where upstream tidal flow balances downstream freshwater flow) to near Georgetown. Since the city of Georgetown was near the point of stagnation, water level there was driven by ocean tidal height rather than river flood stage. The lack of discharge data from the tidal rivers in Georgetown County prevents evaluation of the importance of each of these factors and will limit efforts to make quantitative predictions of future flooding in the county.

INTRODUCTION

Hurricane Florence (September 14–17, 2018) was the most recent occurrence of unprecedented rainfall in Coastal South Carolina over the last four years. The frontal interaction with Hurricane Joaquin in 2015, Hurricane Matthew in 2016, and Hurricane Florence in 2018 produced local rainfall totals larger than had ever been measured prior to the storms. By September 20 the Waccamaw River nears Longs, South Carolina, peaked at 57,500 cubic feet per second (cfs) (USGS Gauge 02110500, 4:15–4:30 p.m., 9/20/2018), which exceeded the previous record following Hurricane Matthew by 137%. The Little Pee Dee River at Galivants Ferry peaked at 64,700 cfs (USGS Gauge 02165000 9:45 a.m., 9/21/2018), which was 110% over the previous record following Hurricane Matthew. In contrast to the previous storms, the path and slow movement of Hurricane Florence caused excessive rainfall in the entire Pee Dee River Basin. Flow from the Upper Pee Dee River Basin at Bennettsville, South Carolina (USGS Gauge 02130561 5:15 a.m., 9/18/2018), of 191,000 cfs greatly exceeded the peak flow measured at that site due to the short period of record. The Bennettsville flow was 87% of the largest peak flow measured on the Great Pee Dee in 1945 at the "Pee Dee at Pee Dee" gauge (02131000). (Refer to Figure 1 and Table 1 for locations.) Given near-record and above-record flooding on three major tributaries to Winyah Bay, record flooding was expected for eastern Georgetown County and the city of Georgetown. However, peak water level at Pee Dee River bridge near Georgetown was 4.14 ft (NAVD88) (USGS Gauge 02136350 1:15–1:45 p.m., 9/30/2018), which corresponds to the peak ocean tide of 3.57 ft (NAVD88) measured during that same period at Springmaid Pier (NOAA Tide Gauge 8331070 12:48 p.m., 9/30/2018).

Two main aspects of the flood will be considered. First, and the most obvious, is the stage or the height of the water surface. The difference between the water surface and the land elevation determines if, or how deeply, any particular spot will flood. Unfortunately, stage is a local value, which, especially on older gauges, refers to a site-specific datum that is arbitrarily set to be lower than the river bottom. The published stage is only meaningful as a correlate to the extent of flooding at any spot. For example, a landowner may know that a stage of 25 ft at the nearest gauge will flood to the edge of his property, a stage of 28 ft will reach his house, and he must evacuate before the stage exceeds 32 ft. This can cause a great deal of confusion since the relation could be the same if the property was 10 ft or 1,000 ft above sea level. To relate water levels from headwaters to outlet, all gauge data must refer to a common datum, and in this paper we will use the North American Datum of 1988 (NAVD88).

The other very useful flood aspect is discharge (often just called flow), or the quantity of water flowing past a point. Ignoring small differences due to a shifting bed, discharge of a non-tidal river is determined by the stage and can be estimated by measuring flow over the range of stages and calculating a stage-discharge relationship (curve). Until recently, discharge measurements were made by dedicated technicians measuring the cross-sectional area and velocity at each stage height, establishing new stage versus discharge points with each increasingly larger flood. Unlike stage, discharge does not decrease in the downstream direction. Ignoring small differences due to evaporation and groundwater infiltration, all the water passing an upstream station must also pass a downstream station. The downstream station will also include flow from ungauged tributaries, which can be estimated by comparing the total volume of upstream and downstream discharge during the entire flood. Continuity in the volume of water means that, in addition to the correlation between stage and flooding, there is causation. Besides the obvious fact that larger upstream floods produce larger downstream floods, there is a direct mathematical relationship between upstream stage, the quantity of water flowing in the river, and downstream stage. These relationships form the basis of all flood modeling.

Discharge can be expressed in a number of units. Pump flows are usually rated in gallons per minute, which is probably the most intuitive unit. One can envision drawing a gallon of water from a faucet in a minute. USGS expresses river flows in cubic feet per second (cfs). A cubic foot contains 7.48 gallons and a minute has 60 seconds, so 1 cfs is 448.8 gallons per minute. River flows of tens to hundreds of thousands of cfs are large but not particularly intuitive. For such large flows, the acre-foot (volume of water to cover 1 acre at a 1-foot depth, or 43,560 cubic feet) becomes a more comprehensible value. If accumulated over a day, each cfs is 1.98 acre-foot. In terms of flooding, 1 cfs flowing into a 1-acre pond will raise the level by 2 ft in a day.

The goal of this paper is to try to explain why large-scale flooding did not occur along the lower Waccamaw River and Winyah Bay. In this paper we present data collected (publicly available at USGS and NOAA websites; USGS, "Science in Your Watershed"; USGS, "Current Water Data"; NOAA-NGS, "NADCON";) during the period of September 10 through October 10, 2018, and discuss that information in relation to our best understanding of the hydraulic forces occurring in the estuary and the portion of the tributary rivers where water level fluctuates in response to the tide. We use terminology of Hoitlink and Jay (2016), where the estuary is the portion of the system where ocean and freshwater mix, and where "tidal river" is the freshwater river where water surface elevation varies with the tide. On the southeastern US Atlantic coast, the upstream limit of the tidal river, "head of the tide" is where a semi-diurnal water surface fluctuation has an average range of 0.2 ft (https://shoreline.noaa.gov/glossary.html). The area examined in this paper is considerably larger than the tidal region and includes a polygon defined by the locations of USGS gauge sites listed in Table 1: from Georgetown to Little River along the coast, to near Longs on the Waccamaw River, Galivants Ferry on the Little Pee Dee River, near Bennettsville on the Great Pee Dee River, and near Effingham on the Lynches River (Figure 1). The tidal reach estimation in Figure 1 could only be accurately estimated for the Waccamaw River where a number of gauges recording both stage and discharge allow an estimate of the extent of tidal fluctuation. On the Little and Great Pee Dee Rivers there are fewer gauges, and a cruder method was used. Ensign et al. (2015) measured a decrease in the erosive power of a river downstream of the head of the tide, while Gardner and Bohn (1980) showed that meanders in tidal creeks are stable. In this region, most county boundaries were drawn in the middle of the larger rivers. That was the case for the Great Pee Dee separating Marion County from Florence, Williamsburg, and Georgetown Counties, and the Little Pee Dee separating Marion and Horry Counties. Since these boundaries were drawn in the late eighteenth and nineteenth centuries, the rivers have meandered and the boundary is no longer in the center of the present river. A simple overlay of the present river and the county boundaries revealed points on the Great and Little Pee Dee Rivers where the boundary and center of the present river coincide. The change from active meandering and stable meanders was used as a crude estimate of the head of the tide.

SITE DESCRIPTION

Winyah Bay is the outlet of the Pee Dee River Basin [Hydrologic Unit Code (HUC) 0304], draining approximately 15,000 sq mi, which is comprised of the upper and lower Pee Dee Basins (HUC 030401, 030402) (USGS, "Science in Your Watershed"). The upper Pee Dee Basin extends from the eastern continental divide near the Virginia border through the central North Carolina Piedmont to the South Carolina border (Figure 1). The lower Pee Dee Basin (HUC 030402) includes the Great Pee Dee River Basin (03040201), Lynches River Basin (03040202), Little Pee Dee Basin (03040204 including the Lumber River Basin 03040203), Black River Basin (03040205), and Waccamaw River Basin (030400206). The Great Pee Dee and Lynches Basins include Sand Hills and Upper Coastal Plain provinces, while the Black, Little

Pee Dee, and Waccamaw Basins are within the Lower Coastal Plain. Although not all listed streams are identified, a relief map of the Pee Dee Basin can be found at http://dnr.sc.gov/geology/esw15/basins3d.html.

METHODS

Hurricane Florence flooding in Georgetown County was primarily due to flooding in the Great Pee Dee, Little Pee Dee, and Waccamaw Rivers. Many of the characteristics of the flooding can be explained with stage and discharge data from 18 USGS gauge stations (Table 1, USGS, "Current Water Data"). Four of the gauges (3, 6, 8, and 11) have long-term records and have been used to estimate flood probabilities, while two (5 and 7) were temporary stage gauges deployed only during the peak of the flood. Discharge was measured in all of the permanent non-tidal gauges (1, 3, 4, 6, 8, and 11) and four of the tidal gauges (9, 11, 12, and 13).

A map of the area of consideration was made in ARC-GIS 10.2 with the ESRI photo basemap, a collaboration of ESRI, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, UDGS, AeroGRID, IGN, and the GIS user community (Figure 1). Land elevations were obtained from SCDNR LiDAR for the counties included. The data frame for the analysis used the SC State Plane projection coordinate system with the US foot as length unit. River distances were calculated with the ARC-GIS distance tool by digitizing straight line segments along the estimated centerline of each river. Sinuosity of the respective rivers was also estimated by using the same tool and digitizing the center of the river valley rather than the channel.

For this paper, data from each gauge were downloaded from the USGS South Carolina Current Water Data website (USGS, "Current Water Data"). From the online map, each gauge location was chosen and the webpage for that gauge opened. From the "Time Series: Current and Historical Observations" page, a beginning date of 9/10/2018 and an ending date of 10/10/2018 were chosen and a tab-separated data set was downloaded. The downloaded file was then copied into an Excel spreadsheet and converted to columns of data for date, time, stage, and discharge. A master dates and time column (to include all 96 quarter-hour intervals for each of the 30 days) was constructed and used to create blank cells for data gaps in each downloaded data set. Most gauge records were recorded at 15-minute intervals, but the Pee Dee at Pee Dee (3) and Pee Dee below Pee Dee (4) were recorded at 30-minute intervals. For graphing, a data set was created for all gauges on the Great Pee Dee Basin (1–10,

Table 1. Summary of data sources used to evaluate flooding associated with Hurricane Florence (September 14–17, 2018). For each gauge location, the station name and number associated with that gauge in Figure 1, the USGS ID number, the published gauge datum elevation, the horizontal and vertical national datum associated with the gauge, and a correction factor applied to published stage to produce elevation relative to NAVD88 are presented.

Station Name and Location Number in Figure 1	USGS ID Number	Gauge Datum Elevation (ft)	Horizontal Datum	Vertical Datum	Correction to Obtain NAVD88 (ft)	Discharge Measured
Pee Dee near Bennettsville 1	02130561	0.00	NAD27	NGVD29	-0.98	Y
Pee Dee near Florence 2	02130810	0.00	NAD83	NAVD88	0.00	N
Pee Dee at Pee Dee 3	02131000	23.54	NAD27	NAVD88	+23.54	Y
Pee Dee Below Pee Dee 4	02131010	14.29	NAD27	NAVD88	+14.29	Y
Pee Dee Below Florence (Hwy 378) 5	335413079261000	0.00	NAD83	NAVD88	0.00	N
Lynches River at Effingham 6	02132000	58.49	NAD27	NGVD29	Not used for height	Y
Lynches River at Hwy 41/51 7	335025079265600	0.00	NAD27	NAVD88	0.00	N
Little Pee Dee at Galivants Ferry 8	02135000	23.95	NAD27	NGVD29	+22.96	Y
Pee Dee near Bucksport 9	02135200	-7.92	NAD27	NGVD29	-8.92	Y
Pee Dee at Georgetown 10	02136350	0.00	NAD27	NAVD88	0.00	N
Waccamaw near Longs SC 11	02110500	5.28	NAD27	NGVD29	+4.23	Y
Waccamaw above Conway 12	02110550	0.00	NAD83	NAVD88	0.00	Y
Waccamaw at Conway 13	02110704	-5.06	NAD27	NGVD29	-6.09	Y
Waccamaw near Bucksport 14	02110802	-14.36	NAD27	NGVD29	-15.36	N
Waccamaw near Pawleys Island 15	021108125	-4.5	NAD27	NAVD88	-4.50	N
Waccamaw at Hagley Landing 16	02110815	-14.14	NAD27	NGVD29	-15.15	N
AIWW at Socastee 17	02110715	10.9	NAD27	NAVD88	-10.9*	N
AIWW on Hwy 9 18	02110777	-11.72	NAD27	NGVD29	-12.04	N

*Change to negative was made as published value produced unreasonable water levels.

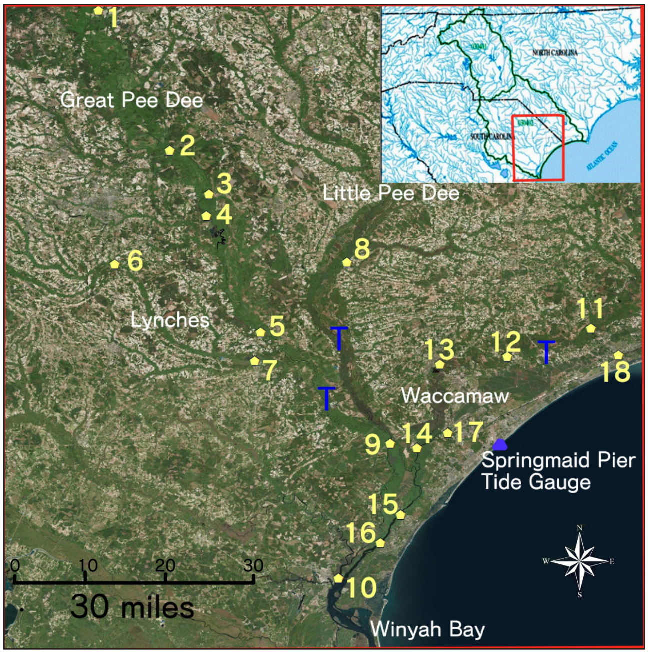

Figure 1. Photomap of a portion of the Lower Pee Dee Basin (HUC 030402) shows the location of USGS gauge sites and NOAA tide gauge where stage and discharge data were collected during Hurricane Florence flooding. The blue "T" on each river indicates an approximate head of the tide.

15, 16) at a 30-minute interval by deleting all quarter-hour readings. This resulted in peak errors generally less than 0.1 ft in stage and less than 500 cfs in flow rates.

For each gauge, the "Summary of all Available Data" page was accessed and the gauge location (i.e., latitude, longitude) and gauge datum elevation were recorded. Since these gauges have differing histories, for the older gauges the stage often refers to a local datum (a convenient zero point such as the bottom of a bridge pier). Also, locations and datum elevations of many of the gauges established during the twentieth century are referenced to the North American Datum of 1927 (NAD27) for a horizontal location and the National Geodetic Vertical Datum of 1929 (NGVD29) for a vertical datum. With the advent of satellite navigation, these have been updated to the North American Datum of 1983 (NAD83) for horizontal location and the North American Vertical Datum of 1988 (NAVD88) for elevation.

All elevations were converted to be relative to the NAVD88 datum. This was done with two web-based services. NADCON (NOAA-NGS) can be used to convert the NAD27 horizontal location to NAD83, and VERTCON (NOAA-NGS) can be used to correct NGVD29 data to the NAVD88 vertical datum. Both programs must be used, as the VERTCON program can only use NAD83 horizontal locations to do the vertical conversion. The datum of each gauge and the stage conversion factor is listed in Table 1.

One discrepancy was found in the data for USGS gauge 02110715, Atlantic Intracoastal Water Way at Socastee, where the gauge datum was listed as 10.92 ft. However, that value produced water levels that were inconsistent with the nearby Waccamaw River gauge at Bucksport. Changing the sign of the published value to a negative produced more consistent elevation data. The negative value was used for this site.

For those gauges where discharges were measured, the downloading and data conversion procedures were the same as the procedure for stage. All flow values were in cfs and recorded in the same 15- or 30-minute intervals as the stage data. Flow data was also converted to an acre-foot volume (60 sec × 15 min/43560 sq ft) for all 15-minute interval data and (60 sec × 30 min/43560 sq ft) for 30-minute data. The sum of these converted results was calculated each day to determine acre-foot per day. In order to estimate accurate daily flow volumes, missing flow readings were estimated by linear interpolation. In most cases, data gaps were fewer than three hours and occurred during linear increase or decrease of flow.

RESULTS

Summaries of the stage, discharge, and water surface slope for the Great Pee Dee and Waccamaw Rivers are presented in Table 2. Stage elevations in the Pee Dee and Waccamaw systems are depicted in Figures 2 and 3. The stage hydrographs of the non-tidal portions of each river demonstrate aspects that are common to all river valley flooding. The flood wave is attenuated as the flood progresses downstream. On the Pee Dee River (Figure 2), this attenuation is easily observed between the Bennettsville (1) and Highway 378 (5) gauges. At Bennettsville, water level rises from 60.38 ft on September 16 to 93.7 ft on September 18, while at Highway 378 it rises from 21.6 ft. on September 16 to 38.35 ft on September 24. The peak at Highway 378 is roughly half as large as the peak at Bennettsville and is delayed by 6 days. Although most of the Waccamaw is tidal at low flow, during the flood this same attenuation is evident in the stage from Longs to Conway (Figure 3).

The characteristics of the stage at each of the tidal gauges can be seen more clearly in Figure 4 during low flow conditions before the storm (September 10–12, 2018). Tidal amplitude is reduced as the tide moves upstream and the times of high and low water are retarded; this is more evident at low tide. On the Pee Dee River, tidal fluctuations were recorded at the Bucksport gauge (9), nearly 40 miles upstream. Tides there are retarded longer than half a tidal cycle so that river high water occurs at ocean low tide. The Bucksport gauge on the Waccamaw River (14) is a similar distance from the ocean (Table 2) and has very similar tidal fluctuation. With a mean daily flow of 4500cfs water flowed upstream for two hours prior to high tide on the Pee Dee at Bucksport (9). Likewise, with a flow of only 120cfs water flowed upstream for four hours prior to high tide at the Above Conway gauge (12).

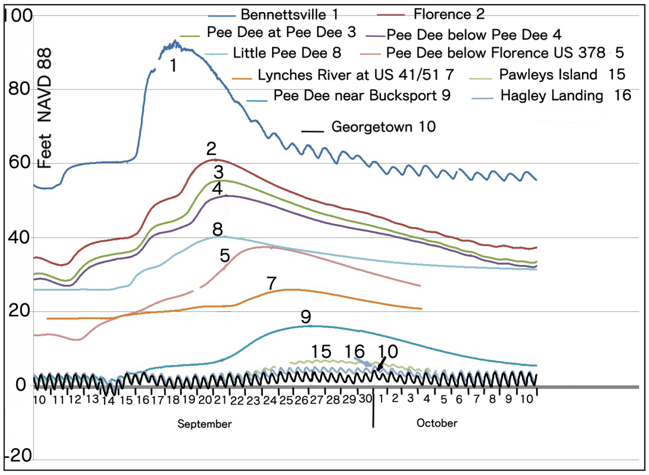

Figure 2. Stage hydrographs for gauges from Georgetown to Bennettsville associated with the Great Pee Dee River. Numbers following the station name refer to locations marked in Figure 1.

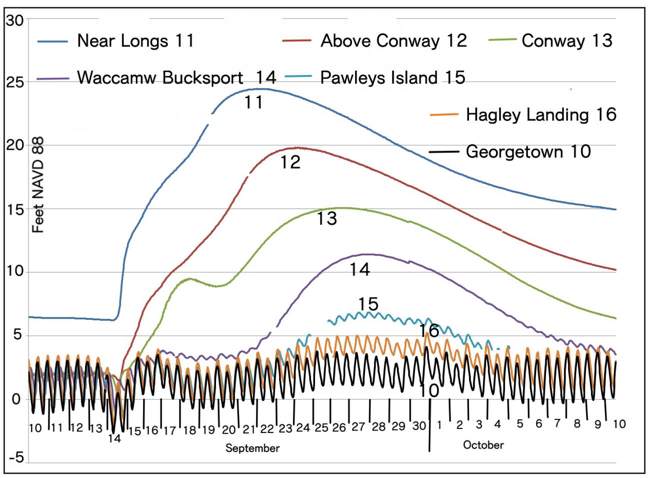

Figure 3. Stage hydrographs for all gauges from Georgetown to Longs associated with the Waccamaw River. Numbers following the station name refer to locations marked in Figure 1.

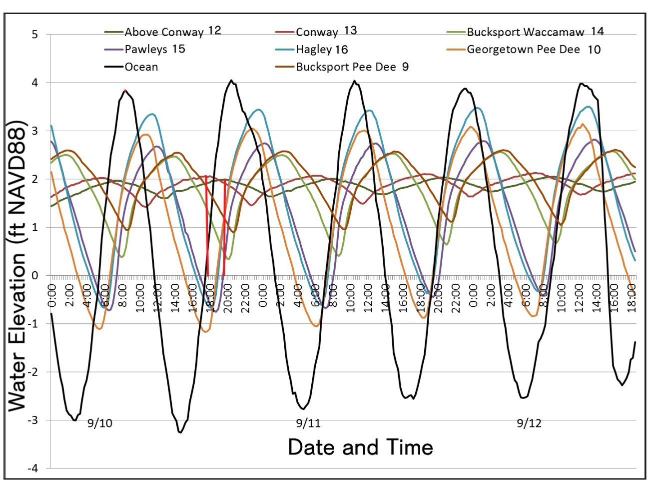

Figure 4. Large scale depiction of stage at gauges with a tidal signature prior to Hurricane Florence. The ocean values were measured at Springmaid Pier while other gauges were at points marked by that number (Figure 1). Note that NAVD88 is slightly above mean tide level at Springmaid Pier.

Discharge hydrographs are depicted as bar graphs of total volume for each day in acre-feet (Figures 5 and 6). Although the graphs are in discreet volumes, daily changes are similar to the stage hydrographs depicted in Figures 2 and 3. However, discharge values reveal the flow of the Little Pee Dee and Lynches tributaries that join the Pee Dee above the gauge near Bucksport. Tributaries to the Waccamaw also result in large flow near Conway. Discharge peaks in the upper non-tidal reaches were reduced and delayed prior to reaching the tidal channels on both watersheds, yet there were prolonged large flows feeding the tidal system above Georgetown. Unfortunately, there was no discharge data recorded at any of the gauges of the tidal river sections in Georgetown County.

DISCUSSION

The first reason for reduced flooding in Georgetown County following Hurricane Florence was the lowering of the flood peaks by floodplain storage. There is very little development in the floodplains of the Pee Dee Basin in South Carolina. Flooding onto these primarily forested floodplains resulted in considerable decline in both the depth of flooding and the peak discharge. The mechanisms of floodplain storage can be easily explained as similar to a checkbook balance, with upstream flow treated as income and downstream flow as expenses, then applied between the Pee Dee below Pee Dee gauge (3) and the Pee Dee near Bucksport gauge (9). Near Bucksport, the flow of the Pee Dee River is made up of flow coming from the Great Pee Dee, Little Pee Dee, and Lynches Rivers shown in Figure 5. By simply accounting for the river discharge at each point, we can see the water that must be stored on the floodplain from September 17 through September 23 and released from the floodplain thereafter (Figure 7). If the excess or deficit is accumulated over time, we can produce a hydrograph of water flooding over the floodplain (Figure 8).

The impact of floodplain storage is quite remarkable in this section of the river. The flooding depth and peak flow rate are smaller at Bucksport despite large additional flow of the Little Pee Dee. The peak was also delayed from September 21 until September 27. By using the gauge elevations, the area of floodplain storage can also be approximated on LiDAR digital elevation models (DEMs) from Florence, Georgetown, Horry, Marion, and Williamsburg Counties (SCDNR, "LiDAR Status") (Figure 9). The approximate flooded area in Figure 9 is 156,000 acres. If the peak floodplain storage (1.2 million acre-feet) in Figure 8 is divided by 156,000 acres, the average peak flood depth works out to be about 7.9 ft on September 24, with actual depths dependent on floodplain topography. Significant portions of the lower areas were cypress and bottomland hardwood forests, along with loblolly pine plantations on the highest elevations. Species in

Table 2. Peak flooding associated with Hurricane Florence(September 14–17, 2018). Peak stage, discharge, and water surface slope as based on river distance. Slopes of peaks of low flow before the storm (September 10) are included.

Station	Distance from Ocean and River Valley Miles		Peak stage (ft NAVD88)	Location Figure 1 Number	Peak discharge (cubic feet per second)	Downstream slope during flood peak (ft/10 miles)	Downstream slope September 10 high tide (ft/10miles)
Ocean	0		3.57				
Georgetown	14.9	14.5	4.14	10		0.38	-0.61
Hagley Landing	22	21.7	5.21	16		1.51	0.61
Pawleys	27.1	26.4	6.82	15		3.16	-1.33
Pee Dee near Bucksport	38.8	37.8	16.07	9	137,000	7.91	-0.07
Pee Dee at Hwy 378	80.8	62.8	38.4	5		5.32	2.66
Pee Dee below Pee Dee	103.8	82.6	51.25	4	139,000	5.59	6.56
Pee Dee at Pee Dee	108.0	85.2	53.25	3	134,000	4.76	3.93
Pee Dee near Florence	117.7	93.7	61.0	2		7.99	4.19
Pee Dee near Bennettsville	161.6	126.6	93.07	1	191,000	7.26	4.44
Waccamaw at Bucksport	39.4	37.6	11.41	14		3.73	-0.16
Waccamaw at Conway	57.1	49.9	15.06	13	49,000	2.06	-0.23
Waccamaw above Conway	73.3	59.3	19.81	12	44,500	2.93	-0.05
Waccamaw near Longs	108.1	71.9	24.45	11	57,500	1.33	1.29

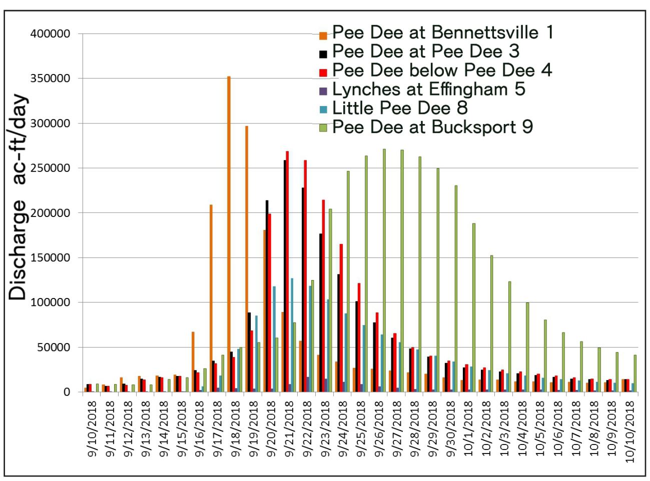

Figure 5. Daily discharges (ac-ft) of gauges on the Pee Dee River.

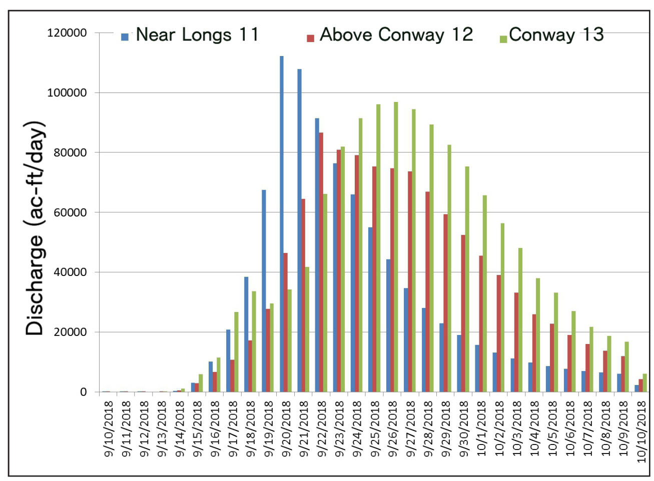

Figure 6. Daily discharges (ac-ft) of gauges along the Waccamaw River.

these timber types are tolerant of short-term flooding (Hook, 1984), so flooding resulted in very little loss in timber value.

The interaction of the ocean, estuary, and tidal river is the least understood aspect of coastal hydrology (Ensign et al. 2012). Much of this lack of understanding is due to the historical and philosophical differences between terrestrial hydrology and coastal hydrodynamics. While terrestrial hydrology originated in the mid-nineteenth century with French engineers concerned with floods (Biswas, 1970), scientific prediction of the tides began in the late nineteenth century with Lord Kelvin's theory of waves and tides in deep water. Much of the development of tidal models was performed by people associated with the English Navy (Darwin, 1901; Doodson, 1921; Ekman, 1993). This historical difference is also reflected in the US government with tidal measurement and prediction done by NOAA under the Department of Commerce, while terrestrial hydrology is primarily done by the US Geologic Survey (USGS) in the

Department of Interior. Although both sciences utilize the same fluid dynamics equations developed by Bernoulli, hydrodynamicists primarily view water movements as waves transferring energy and momentum, while terrestrial hydrologists view water movement as a unidirectional loss of energy as water flows down-gradient.

Tidal prediction and modeling within the ocean and shallow bays have progressed greatly with the advent of numerical modeling and satellite observations in the late twentieth century (Ray et al., 2011). Langbein (1963) found that alluvial estuaries tended to decrease in width at an exponential rate with distance from the ocean. Most estuaries were "funnel shaped" when viewed from above. Saveniji (1992, 2015) has developed analytical solutions to predict tidal movements in smooth "funnel shaped" estuaries and showed that analysis of "equivalent funnel shaped estuaries" can be applied to many real estuaries worldwide. Horrevoets et al. (2004) expanded this analysis to include the influence of freshwater flows. Although these analytical solutions were only valid for steady freshwater input, they did highlight the importance of the point of stagnation, the point where upstream flow from the rising tide exactly matched downstream fresh flow. A critical aspect of the stagnation point was the role of this point in control of water surface level. Downstream of this point, water level is controlled by the height of the tide and the hydraulic shape of the estuary, while upstream of the point, water level is determined by the hydraulic shape of the river and the rate of freshwater flow.

The interaction of flooding and the positioning of the point of stagnation may have been the most important determinant of the water levels in the city of Georgetown and along the lower Waccamaw River. Prior to the storm (Figure 4), tidal fluctuations are present near Bucksport (9) on the Pee Dee River and above Conway (12) on the Waccamaw River. The tidal range decreased and was retarded upstream. Data

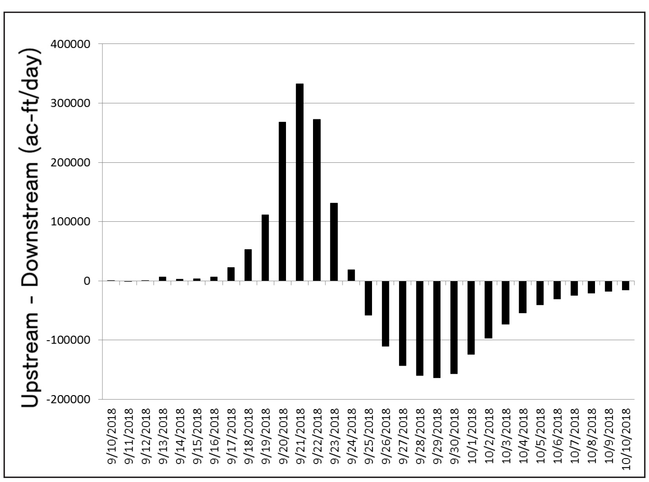

Figure 7. Daily depiction of water quantity (ac-ft) stored on the floodplains of Great and Little Pee Dee Rivers above the gauge near Bucksport, South Carolina, calculated as summed discharge from gauges 4, 6, and 8, minus flow at gauge 9.

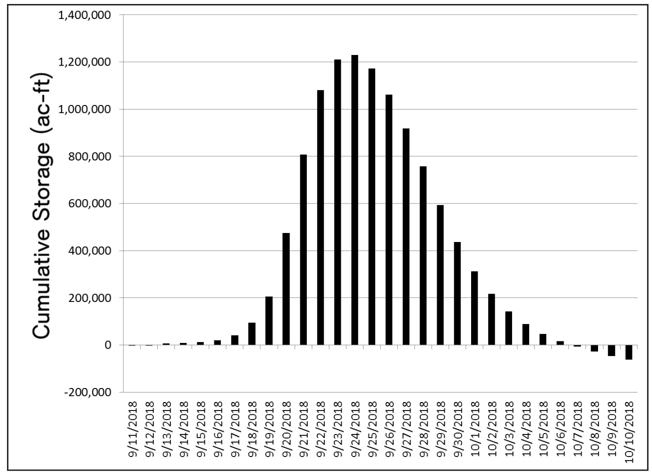

Figure 8. Data in Figure 7 expressed as cumulative storage on the floodplain (ac-ft).

from Winyah Bay are qualitatively consistent with the theory of a funnel-shaped estuary, although Winyah Bay is nothing like a funnel shape. Saveniei (2015) argues that an equivalent funnel-shaped estuary can be used to model a real estuary. Likewise, Horrevoets et al. (2005) results have shown, for an idealized estuary, the water surface slopes upstream from the ocean to the stagnation point, then level near it, and slopes downstream above that point. Their results may be equally valid for Winyah Bay and the connected tidal rivers. Ensign et al. (2015) also found a decrease in slope from the head of the tide to the point of stagnation in well-instrumented tidal rivers in Virginia.

A longitudinal profile of the peak elevations of Winyah Bay and the tidal rivers on September 10 (Figure 10, red triangles)

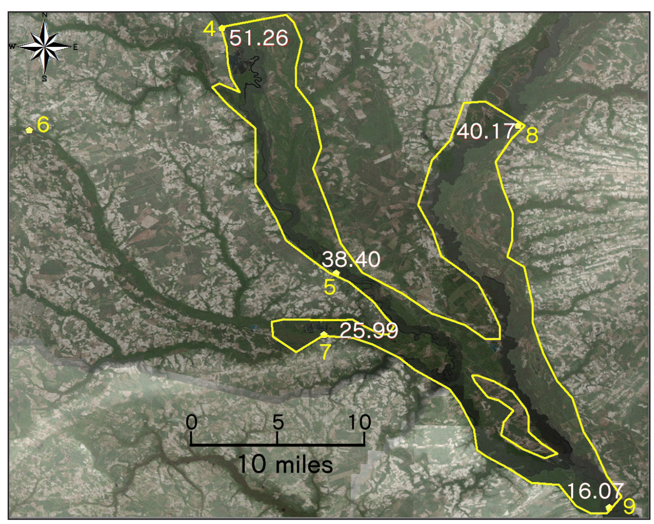

Figure 9. Approximate area of the flooded region (yellow polygon) between gauges 4 and 9. Portion of photomap in Figure 1 with a semitransparent overlay of LiDAR DEMs of Florence, Georgetown, Horry, Marion, and Williamsburg Counties. Yellow numbers are gauge locations (Figure 1; Table 1), and white numbers are peak heights (Figure 2; Table 2) at those locations.

shows clear slopes from the ocean to near Bucksport (9) on the Pee Dee and near Conway (13) on the Waccamaw. On the Pee Dee, there is also a decline in slope between Highway 378 (5) and near Bucksport and the Waccamaw is nearly level between Conway (13) and above Conway (12). Examination of the discharge records near Bucksport (9) show upstream flow for 1–3 hours before high water on September 10–13, with mean daily flows of 4,230–4,170 cfs indicating the stagnation point slightly upstream of that gauge. On September 14, mean flow increased to 7,170 cfs and no upstream flow was measured. Likewise, above Conway (12), upstream flows occurred from 3–4 hours prior to each high tide from September 10–13 with mean daily flows of 114–118 cfs, only on one tide on September 13 with a mean daily flow of 317 cfs, and none on September 14 with a discharge of 1,527 cfs. Clearly the point of stagnation varies with freshwater flow closer to the ocean with higher flow, and it can be estimated by examining the water surface slope. One can extend this reasoning to suggest that for each point along the tidal river and estuary, there is a critical freshwater flow that will equal the upstream tidal flow. For flow below that critical amount, water level is controlled by the tide, and all water moves downstream during the ebbing tide. Above that critical flow, water level is controlled by the freshwater flow rate and will be subjected to flooding much like the rest of the river valley.

The plot of slope during the peak of the Florence flooding (Figure 10, blue diamonds) shows the water surface slope approaches level (< 0.5 ft/10 mi) near the Georgetown gauge (10). This result then suggests that the point of stagnation was very close to Georgetown and thus might explain why water levels there were controlled by the tide level in the ocean. Floodwaters near Georgetown simply flowed out to sea within the tidal channel during each ebbing tidal cycle, much like those at Bucksport when the Pee Dee flow was only 4,500 cfs.

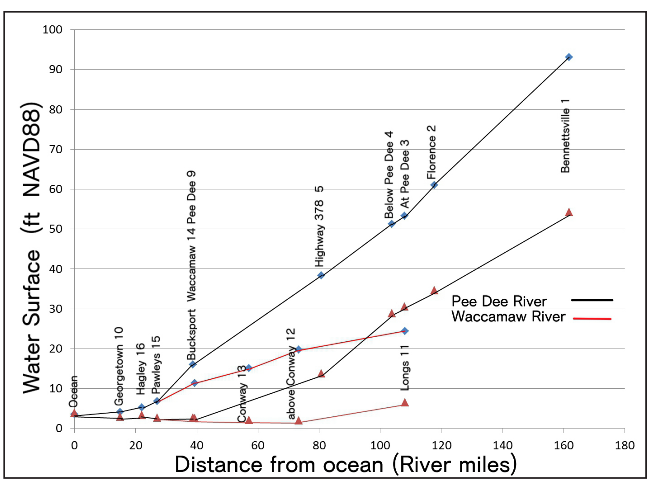

Figure 10. Depiction of peak stage longitudinal profiles during a period of low flow (September 10) in red triangles and during the peak of Florence flooding in blue diamonds. Note that peak stage is not simultaneous at different stations, so these particular profiles do not represent the profile at any particular time.

What was the critical flow when the point of stagnation was near Georgetown? Unfortunately, the lack of discharge data for the gauges in Georgetown County makes that question an item of speculation. As seen in Table 2, the peak flows entering the Waccamaw River/Winyah Bay system were 137,000 cfs and 49,000 cfs from the Pee Dee and the Waccamaw, respectively, and the cumulative flow for the peak on September 26 was 367,900 ac-ft, giving an average flow rate of 185,800 cfs. However, the junction of these two rivers is quite complex, joining in three separate creeks that form loops during tidal flow (Figure 11). The Atlantic Intracoastal Water Way (AIWW, 17, 18; Figure 1) also connects the Waccamaw River near Bucksport (14) to the Atlantic Ocean at Little River. Although the AIWW has a tidal node and does not flow during normal periods, the stage at Socastee (17) provided a head of 2–6 ft above high tide at Little River (18) during the period of September 24 through October 5. Likewise, the stage in the Pee Dee at Bucksport (9) was 2–6 ft above the Waccamaw at Bucksport (14), which was about 6 inches to 1 ft above the AIWW at Socastee (17) (Figure 12). From September 23 through October 5 there was a clear gradient from the Pee Dee at Bucksport (9) through Bull Creek to the Waccamaw at Bucksport (14), a small gradient from there to the AIWW at Socastee (17), and a strong gradient to the Ocean at Little River (Figure 11). Although the waterway is considerably smaller than Winyah Bay, some portion of the 185,800 cfs bypassed Winyah Bay and flowed to the ocean through the AIWW. In addition to not knowing the flood attenuation between Bucksport and Georgetown, we also have little idea as to the amount flowing in the waterway.

CONCLUSIONS

Flooding in Georgetown County during and after Hurricane Florence was mitigated by three factors evident in the discharge and stage data collected by USGS and NOAA. First, the large area of floodplain of the Pee Dee, Lynches, and Little Pee Dee Rivers lowered the peak flow at Bucksport by storing over 1,000,000 ac-ft of water and releasing that water over a period of 10 days. Second, it appears that the tidal channel of the Waccamaw River near Georgetown was large enough to convey the combined flow during the ebbing tide with little change in water surface at high tide. Finally, some water flowed through the AIWW from Socastee to Little River and did not contribute to the flow downstream in the Waccamaw River or Winyah Bay.

The lack of data, especially discharge, in Georgetown County limited the extent of the analysis that could be done on tidal channels below Bucksport on the Pee Dee and below Conway on the Waccamaw. For low flows, presence and location of the tidal stagnation point in both the Waccamaw and Pee Dee Rivers were above the last point of discharge measurement and could be estimated relatively accurately.

Figure 11. Photomap of the junction of the Pee Dee and Waccamaw Rivers. Atlantic Intracoastal Water Way (AIWW, 17) exits Waccamaw near the Bucksport gauge (14).

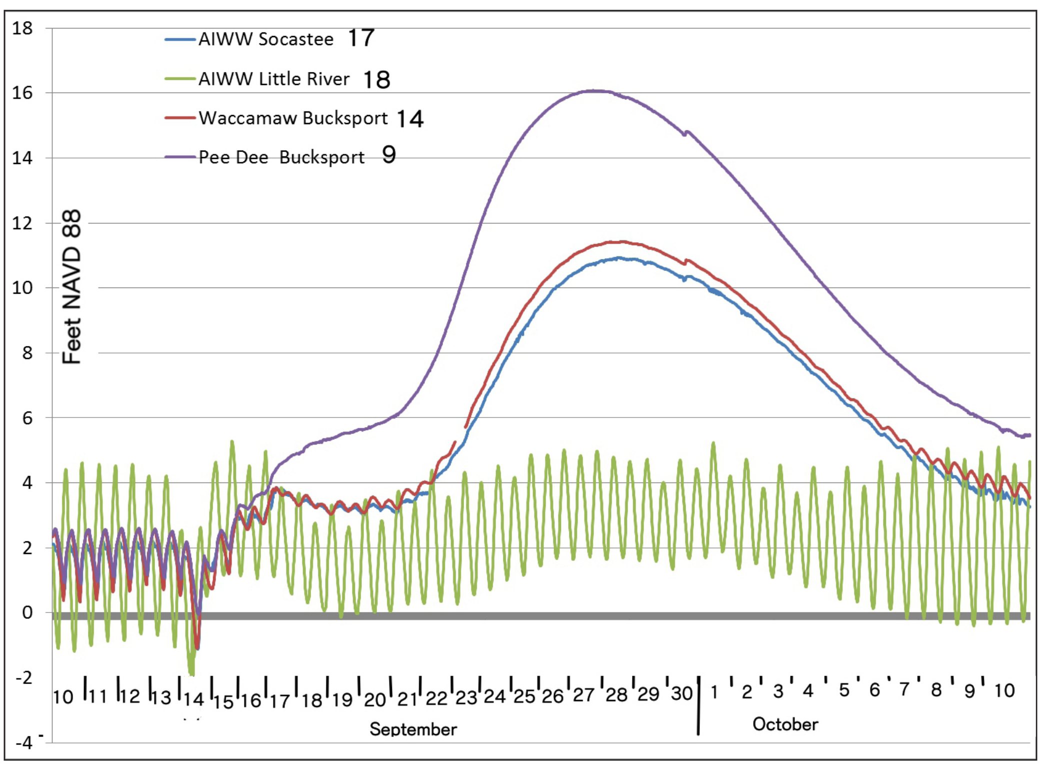

Figure 12. Stage (ft) from Pee Dee to AIWW at Little River.

During the flood, the stagnation point within the bay and the tidal river could only be vaguely estimated by determining water level slope between widely spaced stage gauges. It is obvious that accurate pre-flood modeling was not possible, as the available data do not allow a complete evaluation of the behavior of the flood even after it occurred. This lack of data collection in Georgetown County is critical, as the tidal rivers of the county will be subjected to future floods and changes in tidal flows caused by increasing sea level.

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